Brillouin scattering in high-power narrow-linewidth fiber amplifiers

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Kurzfassung

Laserquellen mit Ytterbium dotierten Fasern als aktivem Medium zählen zu den effizientesten und leistungsstärksten Systemen in der heutigen Lasertechnik. Durch die große Oberfläche und Länge der Fasern und den Betrieb mit geringen Quantendefekten werden leistungslimitierende thermale Effekte minimiert und hohe Ausgangsleistungen mit beugungsbegrenzter Strahlqualität erreicht. Hohe Strahlintensitäten im Kern der Faser ermöglichen einen effizienten Laserbetrieb mit hohen Verstärkungsfaktoren. Relativ kleine Kerndurchmesser und große Längen der Fasern haben jedoch zur Folge, dass nichtlineare Effekte auftreten. Bei der Verstärkung schmalbandiger Laserquellen ist die stimulierte Brillouin-Streuung (SBS) der wesentliche limitierende Prozess. Für die Skalierung der Ausgangsleistung und der damit notwendigen Unterdrückung von SBS wurden in dieser Arbeit experimentelle und theoretische Untersuchungen zur Entwicklung von Brillouin-Streuung in faserbasierten Hochleistungsverstärkern durchgeführt.

In verschiedenen Verstärkerexperimenten wurde Brillouin-Streuung und die Einflüsse auf den Verstärkerbetrieb in Ytterbium dotierten Fasern untersucht. Als Signalquelle diente ein nicht-planarer Ring-Oszillator (NPRO), der schmalbandiges Licht bei einer Wellenlänge von 1064 nm mit 2 W Ausgangsleistung emittiert. Nach der Verstärkung durch aktive Fasern wurden Ausgangsleistungen bis 148 W bei nahezu beugungsbegrenzter Strahlqualität und linearer Polarisation erreicht. Dabei wurde neben einer herkömmlichen Stufenindexfaser erstmalig eine photonische Kristallfaser (PCF) für diese Anwendung untersucht.

Aufgrund der schmalbandigen Emission der Brillouin Streuung von nur einigen MHz Bandbreite, wurden für die spektrale Untersuchung zwei hochauflösende Messverfahren verwendet. Damit konnten erstmals neben der aus stimulierter Streuung und Verstärkung resultierenden spektralen Veränderung andere Einflüsse wie Temperatur und Spannung in Faserverstärkern mit hoher Ausgangsleistung charakterisiert werden. Der Einfluss thermischer Gradienten auf das Brillouin Spektrum stellt in Verstärkern mit hoher Ausgangsleistung einen wichtigen Effekt dar und wird zur aktiven Unterdrückung der SBS eingesetzt. Die in den experimentellen Untersuchungen gewonnenen Erkenntnisse wurden zur Optimierung eines auf Ratengleichungen basierenden, numerischen Modells eingesetzt.

Mit dem numerischen Modell wurden die experimentellen Daten der optischen Leistung und spektralen Entwicklung der Brillouin Streuung rekonstruktiert und seine Gültigkeit in verschiedenen Verstärkerkonfigurationen verifiziert. Damit ist eine Vorhersage der Schwelle für SBS und die Konzeption vergleichbarer Verstärkersysteme weit höherer Ausgangsleistung für schmalbandige Laserquellen möglich.

Schlagwörter: Laser, Faserverstärker, Brillouin Streuung

Abstract

At present ytterbium doped fibers are one of the most efficient high-power laser gain media. The large surface and fiber length and low quantum defect operation minimize thermal effects that limit power scaling and high output power operation with diffraction limited beam qualities can be obtained. High signal intensities in the fiber core enable an efficient, saturated operation. Such high intensities and long fiber length result in nonlinear optical effects that limit the system power handling capacity. In narrow-bandwidth laser systems stimulated Brillouin scattering (SBS) is the most stringent process. In order to increase the optical power and hence mitigate SBS, experimental and theoretical investigations on the evolution of Brillouin scattering in high-power fiber amplifiers have been carried out in this work.

In different amplifier experiments with ytterbium doped fibers Brillouin scattering and its influences on the amplifier operation were investigated. A nonplanar ring-oscillator (NPRO) with a narrow-linewidth output power of 2 W at 1064 nm is amplified up to 148 W with nearly diffraction limited beam quality and linear polarization. Besides a conventional step-index fiber, for the first time a photonic crystal fiber (PCF) was utilized for this application.

Owing to the narrow bandwidth emission of Brillouin scattering of only a few MHz, two high-resolution detection methods have been developed. In this way gain narrowing processes as well as external influences on the spectral shape, such as temperature and strain, can be investigated. Thermal gradients can have a strong effect on the Brillouin gain spectrum in high-power amplifier systems and are applied to suppress SBS. The experimental data obtained from these investigations have been incorporated in a numerical model based on coupled rate-equations.

The numerical model is used to reproduce the experimentally observed optical power and spectral evolution of the fiber amplifier signals and Brillouin scattering and its validity is verified in different amplifier configurations. With this model a prediction of the SBS threshold can be made and design concepts for narrow-linewidth fiber amplifier systems with higher output power can be developed.

Key words: Laser, Fiber amplifier, Brillouin scattering

Contents

1. Introduction

Narrow-linewidth laser sources have become more and more important in various fields of application. Most prominent applications are optical fiber communication networks [1], strain and temperature fiber-optic sensors [2, 3] and scientific areas of research such as cooling and trapping of atoms [4].

Stable narrow-linewidth laser emission is obtained from distributed feedback or external-cavity semiconductor lasers [5], ytterbium or erbium doped fiber lasers [6] and solid-state micro-chip [7] or non-planar ring oscillators (NPRO) [8]. Single-frequency operation with only one resonant longitudinal laser mode and a minimization of external and internal noise sources enables a laser operation with a linewidth of only a few kHz in free-running operation and even sub-Hz linewidth with active stabilization to high-finesse Fabry-Pérot reference cavities [9–11].

Some applications such as interferometers for gravitational-wave detection [12] or the formation of artificial guide-stars for telescopic imaging systems in astronomy science [13] require a large output power of several ten to hundreds of watts. Future generations of gravitational-wave detectors even aim for 1 kW of laser output power with nearly diffraction limited beam quality and linear polarization. These power levels with a stable single-frequency, low noise operation cannot be obtained directly from aforementioned laser oscillators [14]. Therefore, different amplification concepts have been developed in the past to scale the available output power while maintaining the required laser beam characteristics. These laser systems most commonly comprise solid-state lasers injection-locked to a narrow-linewidth master-oscillator [15]. Although high output power of up to 195 W have been demonstrated, such solid-state laser setups are quite complicated and inefficient. Further power scaling is difficult due to thermo-optical effects inducing aberrations and depolarization.

An alternative amplification scheme for narrow-linewidth laser sources using rare-earth doped fused silica fibers has been demonstrated with more than 400 W of output power [16]. In recent years these potentially compact and robust systems have gained much attention in the research field of coherent beam combining of several laser sources by an active phase control to reach output power levels with multiple kilowatts needed for heavy industry and military applications [17]. In fiber laser systems thermal limitations are greatly reduced owing to large fiber lengths and surface areas. However, long interaction lengths and small mode-field areas enhance nonlinear effects that prohibit scaling to larger output power. For narrow-linewidth signal amplification stimulated Brillouin scattering (SBS) becomes the dominant limitation. To some extend SBS can be suppressed by increasing the fiber core size and decreasing fiber length using highly doped large mode-area (LMA) fibers. Broadening of the Brillouin scattering spectrum by temperature and strain gradients or varying doping distributions along the fiber can further reduce the effective Brillouin gain. In high-power fiber amplifier systems particularly temperature gradients induced by absorbed pump light play an important role for the spectral evolution of Brillouin scattering spectra. Understanding and modeling spectral broadening mechanisms of Brillouin scattering is therefore essential for further increasing the output power of narrow-linewidth fiber amplifier systems.

Although great progress has been made to mitigate optical nonlinearities in optical fibers, SBS still represents the most stringent limitation in narrow-linewidth high-power fiber amplifier systems. For this reason this work is focused on the investigation of Brillouin scattering and its effect on the fiber amplifier operation. In different high-power ytterbium doped fiber amplifier configurations operated with up to 148 W of output power the evolution of the Brillouin scattering power and spectra is experimentally detected and theoretically described with a numerical model.

Organization of the thesis

The outline of this thesis is as follows. Chapter 2 provides a general overview over the concept of high-power fiber amplifiers and shortly reviews research group activities in the field of narrow-linewidth fiber amplifier systems and detection techniques for Brillouin scattering. In Chapter 3 the theoretical background for Brillouin scattering in passive and active fibers is introduced with a numerical model based on coupled rate-equations describing the amplifier signal and pump light distributions including the growth of Brillouin scattering. In Chapter 4 the fiber amplifier setup is presented. Chapters 5 and 6 describe results obtained from a high-power fiber amplifier operated with an ytterbium doped step-index and a photonic crystal fiber (PCF) in different amplifier pump configurations. In Chapter 5 general amplifier characteristics are addressed with the spectral, power, polarization and beam quality properties of the amplified signals. Chapter 6 contains the investigation of Brillouin scattering and its influences and limitations on the fiber amplifier operation. Brillouin scattering power and the spectral evolution is experimentally detected and compared with results obtained from numerical modeling including the thermally induced distortion of the Brillouin scattering spectra. In Chapter 7 different approaches for the suppression of SBS are presented and in some parts investigated with the developed experimental and theoretical tools giving directions for future work. Finally, Chapter 8 contains the summary and conclusion of the thesis.